DWARF GALAXIES AND THE ORIGIN OF INTRACLUSTER MEDIUM

Biman B. Nath[1] and Masashi Chiba[2]

[1]Inter-University Center for Astronomy & Astrophysics, Post Bag 4, Pune 411007, India

[2]Astronomical Institute, Tohoku University, Aoba-ku, Sendai 980-77, Japan

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ABSTRACT

Following the recent suggestion that it is dwarf galaxies in clusters – as opposed to large ellipticals – that provide the intracluster gas, we estimate the metallicity of the intracluster medium (ICM) in such a case. We derive analytical expressions for the fraction of mass of dwarf galaxies that is ejected, and estimate the metallicity of the resulting intracluster gas. We find that the metallicity resulting from this hypothesis is adequate only for clusters with low-metallicity gas. Since galactic winds from dwarf galaxies occur much earlier than those from ellipticals, due to the smaller binding energy of the gas, we show that the gas ejected by dwarf galaxies is enriched mostly by Type II supernovae, as opposed to Type I supernovae in the case of large galaxies. We further point out that the gas in small scale structures, which never cools and forms stars due to low temperatures and, consequently, large cooling time scale, gets dispersed in the process of hierarchical clustering, and is incorporated as the diffuse intracluster gas. We show that this process can provide enough hot gas to be compatible with X-ray observations in rich clusters.

Subject headings: Galaxies : abundances – Galaxies : clustering – Galaxies : evolution – Galaxies : intergalactic medium

1. INTRODUCTION

The existence of hot gas in clusters of galaxies was established from X-ray observations almost two decades ago, and so was its metallicity, especially from the emission lines of Fe, Si, S, Mg and O (e.g., Sarazin 1988). The amount of the hot gas has been inferred to

be a substantial fraction of the total gravitational mass of clusters (e.g., White et al.1993). For the origin of this gas, several hypothesis have been put forward, the most pursued one being that of galactic winds from elliptical galaxies driven by supernovae (Arimoto & Yoshii 1987; Matteucci & Tornambè 1987; David et al.1990).

Several authors have, however, found that the amount of gas expelled from the visible ellipticals and S0 galaxies is not adequate to account for the total gas mass (David et al.1990; Matteucci and Vettolani 1988; Okazaki et al.1993). A large portion of the ICM gas, even as large as 90% of it, has therefore been thought to be primordial. This interpretation, coupled with the fact that the ratio of the intracluster gas mass to the stellar mass in the galaxies is higher in rich clusters, has led to the idea that galaxy formation is less efficient in rich clusters (David et al.1990; Matteucci and Vettolani 1988).

The metallicity of the ICM gas has been estimated by various authors from the hypothesis that the metals are produced and expelled in galactic winds from ellipticals. Chemical evolutionary models of ellipticals have been used to predict the metallicity (e.g., Arimoto & Yoshii 1987; Matteucci & Tornambè 1987). Okazaki et al.(1993) found that these models are adequate to explain the observed total mass of iron in the Virgo cluster, but not to explain the total gas mass. Arnaud et al.(1992) defined a dimensionless ratio of iron mass to that of the stars in the galaxy, to analyze the data, and came to the conclusion that one needed a bimodal star formation in cluster galaxies. Renzini et al.(1993) found this idea rather ad hoc, and, introducing another ratio, that of the iron mass to blue light, they found constraints from the data on the yields of Type I and II supernovae rate that may explain the observations. It seems, therefore, that no single model satisfactorily explains the iron mass (or the metallicity) and the total gas mass of ICM, simultaneously.

Recently, Trentham (1994) has suggested that if dwarf galaxies, at the lower end of the luminosity function, are numerous, i.e., if the index of the Schechter luminosity function $\alpha \lesssim -1.7$, as is seen in some clusters, then they may supply enough gas. These galaxies, with shallow gravitational potential wells, and with small binding energy of the gas, are vulnerable to huge mass losses through winds driven by supernovae explosions from the first generation of star formation (Larson 1974; Saito 1979). Dekel & Silk (1986) showed that galaxies with velocity dispersion less than ~ 100 km s^{-1} would lose much of their gas due to large galactic winds, and become low surface brightness dwarf galaxies. Trentham (1994) argued that if a fraction $\gamma \sim 0.05 - 0.33$ of the total mass of the galaxy is expelled, and if the index of the Schechter luminosity function $\alpha \sim (-1.9) - (-1.7)$, for masses $10^4 - 10^{11}$ M$_\odot$, then the amount of gas mass expelled can account for the total gas mass in the ICM.

One of the tests of this interesting model lies in the resulting metallicity of the ICM gas. Since the galactic winds from dwarf galaxies (of total mass $\lesssim 10^{11}$ M$_\odot$) occur in a time scale $t \lesssim 10^9$ yr, Type I supernovae can not contribute substantially to the metallicity. We

suggest here that the hypothesis of dwarf galaxies as sources of ICM gas leads necessarily to the dominance of Type II supernovae as the origin of the metals in ICM. In this paper, we estimate the total metallicity of the ICM resulting from galactic winds from dwarf galaxies using more physical values of γ, rather than a universal number for all galaxies, and we derive the relations between the metallicity and various parameters of star formation.

The structure of the paper is as follows: In §2 we calculate the galactic wind epoch for dwarf galaxies and the mass of iron that is contributed by individual galaxies. In §3, the total mass of iron in the intracluster gas is estimated using the mass function of galaxies. We discuss the nature of the metallicity of ICM in §4. In the paper, we write the present day Hubble constant as $H_0 = 50h_{50}$ km s^{-1} Mpc^{-1}.

2. GALACTIC WIND FROM DWARF GALAXIES

Galactic winds are thought to be initiated when the thermal energy of the gas in the parent galaxy exceeds its binding energy. Below, we will consider galaxies with masses below $M_T \sim 10^{11}$ M$_\odot$, where M_T denotes the total mass. We will assume that a fraction $(1-g)$ of the mass is in the form of dark matter, *i.e.*, the mass of gas (M_g) and that of stars (M_s) comprise a fraction g of the total mass. A few million years after the onset of star formation, the first generation of supernovae begins to explode (the life time of a 100 M$_\odot$ star is $\sim 3.2 \times 10^6$ yr), and they put energy into the interstellar medium.

The energy in the supernovae blastwaves is turned into the thermal energy of the gas, as the supernovae remnant (SNR) shells overlap and the thermal gas inside the shells interacts with the ambient gas in the ISM. (The energy in the dense shell is quickly radiated away and does not contribute much in pumping energy into the ISM gas.) The radii of SNR expand as (Cox 1972)

$$\begin{aligned} R_{SNR}(t) &= R_0 (t/t_{rad})^{2/5}\,, \quad \text{for } t < t_{rad} \\ &= R_0 (t/t_{rad})^{2/7}\,, \quad \text{for } t > t_{rad} \end{aligned} \tag{1}$$

Here $R_0 = 0.039\, n^{-0.4}$ kpc and n is the particle density. The total energy liberated in a typical supernovae is assumed to be 10^{51} ergs. Half of the thermal energy of the SNR is radiated away after a time t_{rad}, which, for primordial gas, is approximately equal to $1.7 \times 10^5 n^{-0.49}$ yr for a primordial gas (Babul & Rees 1992). For a mildly enriched gas, $t_{rad} \sim 0.9 \times 10^5 \lambda^{-5/17} n^{-9/17}$ (using a cooling rate of $3 \times 10^{-18} \lambda T^{-1} n^2$ ergs cm^{-3} s^{-1}, as in Dekel & Silk 1986), where λ represents the metallicity of the gas ($\lambda = 1$ for $Z = 0.01$, and higher for larger value of Z). Since these two time scales are within a factor of order unity, we will use the one for a primordial gas for simplicity.

If we define (as in Babul & Rees 1992) t_{snr}, the time scale for the overlapping of SNRs, as the time when the remnant shells occupy $\sim 60\%$ of the total volume, then t_{snr} can be estimated in the following way. We use for the radius of the galaxy, the expression derived by Saito (1979) (or. e.g., Matteucci & Tornambè 1987), which is valid over a large range of masses, from globular clusters to large ellipticals, *viz.*,

$$R = 1.2 \times 10^5 \Big(\frac{M_T}{10^{12} M_\odot}\Big)^{0.55} \quad \text{pc} \,, \tag{2}$$

where M_T is the total mass of the elliptical galaxy. (This is close to the estimate of the radius of the starburst region of dwarf galaxies in Babul & Rees 1992.) We assume a constant star formation rate for analytic simplicity, and write the star formation rate as $\dot{M}_* \approx (\tau g M_T / t_{ff})$, where $t_{ff} = 1.9 \times 10^7 g^{1/2} n^{-1/2}$ yr is the free fall time of the gas, and $\tau (< 1)$ is the efficiency of star formation. We will see later that the final results of the metallicity of ICM do not depend on τ. The rate of supernovae is given by the $\nu = 10^{-35} \nu_{50}$ per gram, where ν_{50} refers to one supernova per 50 $\mathrm{M}_\odot$ (see also, Dekel and Silk 1986). Therefore, the number of supernovae in time t is given simply by $N_{SN}(t) = \nu \dot{M}_* t$.

The rate of supernovae, as denoted by ν, of course depends on the slope of the initial mass function (IMF). For an IMF with slope x [$\phi(m) \propto m^{-x} dm$], the factor ν_{50} can be written as,

$$\nu_{50} = 50 (\frac{x-1}{x}) \Big(\frac{1}{M_{l,sn}^x} - \frac{1}{M_u^x} \Big) \Big(\frac{1}{M_l^{x-1}} - \frac{1}{M_u^{x-1}} \Big)^{-1} \,, \tag{3}$$

where M_l and M_u are the lower and upper limits of masses of stars in the main sequence, and $M_{l,sn}$ is the lower limit of the mass for the progenitor star for a Type II supernova (all in the units of $\mathrm{M}_\odot$). For $M_l = 0.1, M_u = 100$, and $M_{l,sn} = 8$, we get $\nu_{50} \sim 0.37$ (for $x = 1.35$, Salpeter IMF), and $\nu_{50} \sim 0.90$ (for $x = 0.95$). The term ν_{50}, therefore, succinctly expresses four important parameters ($x, M_l, M_u, M_{l,sn}$) and it will be useful in comparing our results later with the numerical results of previous workers.

The timescale of the SNR collision, t_{snr}, can then be estimated as (in the units of 10^9 yr),

$$t_{snr} \approx 6 \times 10^{-3} n^{0.13} \Big(\frac{\nu_{50}}{0.35} \Big)^{-0.54} \Big(\frac{g}{0.1} \Big)^{-0.27} \Big(\frac{M_T}{10^{12} \, M_\odot} \Big)^{0.35} \quad \text{Gyr} \,. \tag{4}$$

Larson (1974) showed that the fraction of the energy of the blast ($= E_{SN}$) that is finally imparted to the gas is $\eta \sim 0.1$ (see also Babul & Rees 1992), when the remnant shells overlap. We will see below that t_{snr} in eqn (4) is much shorter than the time scale over which the galactic winds are excited. Therefore, the assumption that $\eta \sim 0.1$ is valid, since the whole galaxy would be pervaded by SNRs by the epoch of galactic winds.

As the continuing SNR collisions heat up the gas, the thermal energy content of the gas (E_{th}) increases as,

$$
\begin{aligned}
E_{th}(t) &= 0\,, & t &< 3.2\times 10^6\text{yr}\,,\\
&\approx \eta E_{SN}\nu \dot{M}_* t\,, & t &\gg 3.2\times 10^6\text{yr}\,.
\end{aligned}
\tag{5}
$$

The epoch of the onset of galactic wind, t_{gw}, is defined as the time when the thermal energy of the gas exceeds the binding energy, i.e., $E_{th}(t_{gw}) \geq E_{bin}(t_{gw})$. [We will neglect the effects of stellar winds here (see Gibson 1994).] We take the binding energy of the gas as (Saito 1979; also, eqns (1) and (18) of Arimoto and Yoshii 1987 for $g \ll 2$),

$$
E_{g,bin} \approx 1.5\times 10^{55}(\frac{g}{0.1})\Big(\frac{M_T}{10^9\ M_\odot}\Big)^{1.45}\quad \text{erg}\,. \tag{6}
$$

As noted by previous workers, the energy accumulated in the gas in dwarf galaxies exceeds the binding energy of the gas even when a small fraction of the gas is turned into stars ($M_s \lesssim M_g$) (Larson 1974; Saito 1979; Dekel & Silk 1986). We have accordingly assumed here that $M_s \lesssim M_g$. Eqns (5) and (6) then give,

$$
t_{gw} \approx 8.2\times 10^{-3} n^{-1/2} g^{1/2}\Big(\frac{\eta}{0.1}\Big)^{-1}\Big(\frac{\nu_{50}}{0.35}\Big)^{-1}(\frac{\tau}{0.5})^{-1}\Big(\frac{M_T}{10^9\ M_\odot}\Big)^{0.45}\ \text{Gyr}\,. \tag{7}
$$

This time scale can also be written as

$$
t_{gw} \approx 9\times 10^{-3}\Big(\frac{\eta}{0.1}\Big)^{-1}\Big(\frac{\nu_{50}}{0.35})^{-1}\Big(\frac{\tau}{0.5}\Big)^{-1}\Big(\frac{M_T}{10^9\ M_\odot}\Big)^{0.775}\ \text{Gyr}\,, \tag{7a}
$$

using the density of gas as indicated by the radius from eqn (1). Note that t_{gw} given above is the time taken by SNRs to excite the galactic wind, *after* the first generation supernovae explode, *i.e.*, after $\sim 3.2\times 10^6$ yr. Therefore, to compare with the values obtained numerically by previous workers, *e.g.*, Yoshii & Arimoto (1987, Fig.1), Matteucci & Tornambè (1987, Table 1), one should add $\sim 3.2\times 10^6$ yr to the t_{gw} from eqn (7), to find the *age* of the galaxy at the time of the galactic wind. The numbers from eqn (9) and those in the previous numerical works are consistent within a factor of a few. However, eqn (7) should not be taken too literally for larger masses ($M_T \gtrsim 10^{11}$ $M_\odot$), for which the assumption of constant supernova rate fails. But for dwarf galaxies ($M_T \leq 10^{11}$ $M_\odot$) this assumption is a reasonable one, since the time scale of the galactic wind is much shorter for these galaxies than the time scale of the decline of the supernovae rate after the first peak (Matteucci & Greggio 1986).

It can also be seen from the supernovae rates of Type I and Type II, as computed by Matteucci & Greggio (1986), that SN Is do not begin to contribute substantially to the

enrichment of the gas until after a few times 10^8 yr. This is larger than the galactic wind time scale for galaxies of our interest. Therefore, to calculate the metallicity of the gas expelled by the dwarf galaxies in clusters, we will only consider Type II supernovae.

Renzini et al.(1993) compared the amount of iron produced in SNII, as predicted by various models, and found that an average amount of ~ 0.07 M$_\odot$ of iron is produced per SN II, and that it is fairly independent of the slope of IMF. We write the total amount of iron in the galaxy at the time of the galactic wind as, $M_{Fe} \sim 0.07\nu \dot{M}_* t_{gw}$, using t_{gw} from eqn (9). Approximately, the stars that form *within* $\sim t_{gw}$ after the onset of star formation are the ones that become supernovae *before* the gas is ejected out of the galaxy, and only those stars get to enrich the gas in the galactic wind. This yields,

$$\begin{aligned} M_{Fe} &\sim 0.07\nu \dot{M}_* t_{gw} \quad (M_\odot) \\ &\sim 1.05 \times 10^4 \Big(\frac{\eta}{0.1}\Big)^{-1} \Big(\frac{g}{0.1}\Big) \Big(\frac{M_T}{10^9\ M_\odot}\Big)^{1.45} \quad M_\odot\ . \end{aligned} \tag{8}$$

The average metallicity of the galaxy at the epoch of galactic wind, is then given by [dividing eqn (8) by gM_T, since the total content of iron would be shared by gas and the stars],

$$\frac{Z_{Fe}}{Z_{\odot,Fe}} = \frac{M_{Fe}}{gM_T Z_{\odot,Fe}} \sim 0.056 \left(\frac{\eta}{0.1}\right)^{-1} \left(\frac{M_T}{10^9 M_\odot}\right)^{0.45} . \tag{9}$$

We have used $Z_{\odot,Fe} = 1.89 \times 10^{-3}$ (Renzini et al.1993). The values predicted by the above equation match well those from Fig.1 of Yoshii & Arimoto (1987) for galaxies $M_T \lesssim 10^{11}$ M$_\odot$ (see also Arimoto & Yoshii 1987, Matteucci & Tornambè 1987). However, one should remember the different assumptions adopted by these authors when comparing the results (e.g., the limits on the masses of supernovae progenitors, slope of IMF etc.). We find that the values given by our equations are within a factor of a few from previous numerical results. Moreover, the equations above are more transparent with all the dependences shown explicitly, than the numerical results.

We can estimate the gas mass in the wind following Larson (1974). We define the gas mass and mass which has formed into stars, as M_g and M_s, respectively. The binding energy of the gas is $\frac{E_{g,bin}}{M_g} \sim 1.5 \times 10^{47} \Big(\frac{M_T}{10^9\ M_\odot}\Big)^{0.45}$ erg M$_\odot^{-1}$ [see eqn (6)]. The energy in the gas can be estimated as $10^{48} (\frac{\nu_{50}}{0.5})(\frac{\eta}{0.1}) M_s$ erg, for a typical supernova energy of 10^{51} erg. This means that gas will escape from the galaxy when $\frac{M_g}{M_s} \sim 6.67 \Big(\frac{M_T}{10^9\ M_\odot}\Big)^{-0.45} (\frac{\nu_{50}}{0.5})(\frac{\eta}{0.1}) \sim \Big(\frac{M_T}{6.78 \times 10^{10}\ M_\odot}\Big)^{-0.45} (\frac{\nu_{50}}{0.5})(\frac{\eta}{0.1})$. Therefore, remembering that $gM_T = M_g + M_s$, one can write the fraction of mass that is expelled from dwarf galaxies, as

$$\gamma = \frac{M_g}{M_T} \approx 0.1 \left(\frac{g}{0.1}\right) \frac{(\frac{M_T}{6.78 \times 10^{10}\ M_\odot})^{-0.45} (\frac{\nu_{50}}{0.5})(\frac{\eta}{0.1})}{1 + (\frac{M_T}{6.78 \times 10^{10}\ M_\odot})^{-0.45} (\frac{\nu_{50}}{0.5})(\frac{\eta}{0.1})} . \tag{10}$$

However, this expression for γ is incorrect at the low mass end, because it predicts an unrealistically large value. The above expression neglects the fact that a lot of mass is locked up in low mass stars at the time of the explosion of the first generation supernovae, and it underestimates the mass of stars at the time of the galactic wind. To take this into account, we first note that the galactic wind for galaxies smaller than $gM_T \lesssim 10^7$ $M_\odot$ occurs soon after the first generation of supernovae explode. We then note that the fraction, m_l, of the stellar mass (M_s) that is in low mass stars, can be written in term of the IMF slope x, as

$$m_l = \left(\frac{1}{M_l^{x-1}} - \frac{1}{M_{l,sn}^{x-1}}\right)\left(\frac{1}{M_l^{x-1}} - \frac{1}{M_u^{x-1}}\right)^{-1}. \tag{11}$$

For M_l, M_u, and $M_{l,sn} = 0.1$, 100, and 8 $M_\odot$, respectively, $m_l = 0.86$ ($x = 1.35$) and $m_l = 0.59$ ($x = 0.95$). Now, the gas mass in the galaxy decreases due to star formation as,

$$\frac{d\,M_g}{dt} = -\tau\left(\frac{M_g}{t_{ff}}\right) = -\tau\left(\frac{1}{2.1\times10^7\ \mathrm{yr}}\right)\left(\frac{M_T}{10^9 M_\odot}\right)^{-0.325} M_g\,, \tag{12}$$

where we have used the earlier expression for the star formation rate, and used a value of n that is given by eqn (2) for ionized gas. The mass of gas that remains in the galaxy after $t \sim 3.2\times10^6$ yr, the epoch of the first generation supernovae ($\sim$ life time of very massive stars) is given by,

$$M_g' = gM_T \exp\left(-0.16\tau\left(\frac{M_T}{10^9 M_\odot}\right)^{-0.325}\right). \tag{13}$$

However, this neglects the fact that by the time of the first generation supernovae, the massive stars [of total mass, $(1-m_l)M_s$] would return most of their mass back into the galaxy. Therefore, the actual gas mass $M_g = M_g' + (1-m_l)(gM_T - M_g')$. This gives us an expression for γ that is more realistic for low mass galaxies,

$$\gamma = g\left[1 - m_l\left[1 - \exp\left(-0.16\tau\left(\frac{M_T}{10^9 M_\odot}\right)^{-0.325}\right)\right]\right]. \tag{14}$$

We will use a value of γ that is smaller of the two values predicted by eqns (10) and (14).

The resulting γ is plotted against galactic masses at the present time, $M = M_T(1-\gamma)$, in Fig.1(a). It shows a maximum around $M \sim 10^{8-9} M_\odot$: a large amount of gas is lost from such typical dwarf galaxies. For larger galaxies, the deeper gravitational potential does not allow the hot gas to escape, while for smaller galaxies, most of the gas is converted into stars prior to galactic wind. These values of γ are physically more realistic than the constant γ for galaxies of all masses used by Trentham (1994).

Figure 1(b) shows the corresponding iron abundance of expelled gas in units of the solar value. Smaller galaxies with $M \sim 10^{10} M_\odot$ have less time to enrich the gas ($t_{gw} \lesssim 10^8$ yr), giving a low metallicity, of order less than 0.5 $Z_\odot$. If the conversion efficiency of the blast energy into the gas, denoted as η, is lowered, the epoch of galactic wind is prolonged and thus the metallicity is increased. The mass of expelled iron is estimated as $\gamma M_T Z_{Fe} = \frac{\gamma}{1-\gamma} M Z_{Fe}$, and the resulting iron masses for $M \sim 10^{9-11} M_\odot$ are in good agreement with those numerically derived by Matteucci & Tornambè (1987) and David et al.(1990).

3. HOT GAS AND IRON IN COMA CLUSTER

Having derived the physically plausible expressions for the ejected gas fraction γ of initial total mass and its iron metallicity Z_{Fe} in each dSph galaxy, we estimate the total amount of hot gas and iron in the ICM. Following Trentham (1994), we use a Schechter luminosity function $\phi(L)$ with the faint-end slope of α, *i.e.*, $\phi(L)dL = \phi^* \exp\left(-\frac{L}{L^*}\right)\left(\frac{L}{L^*}\right)^\alpha \frac{dL}{L^*}$. Also, as in Trentham (1994), we use a scaling law for the mass-to-light ratio, $(M/L) \propto L^\beta$, for dSph galaxies. The characteristic luminosity L^*, at the knee of Schechter function, is $\sim 1.42 \times 10^9 h_{50}^{-2} L_\odot$ for dSph galaxies (Sandage et al. 1985). Converting into the mass function with $M^*/L^* = 15$ for the characteristic mass (Trentham 1994) and using γ, we derive the total mass of gas ejected from dSph galaxies as

$$M_{gas} = N^* M^* \int_{M_-}^{M_+} \frac{\gamma}{1-\gamma} \exp\left(-\left(\frac{M}{M^*}\right)^{1/(\beta+1)}\right)\left(\frac{M}{M^*}\right)^{(\alpha+1)/(\beta+1)} \frac{dM}{(1+\beta)M^*}\ , \qquad (15)$$

where M denotes the present-day galaxy mass, and N^* is a characteristic number of dSph galaxies, which is equal to 302.6 for Coma (Trentham, private communication). The integral is performed over all masses of dSph galaxies between M_- and M_+. Similarly, the final metallicity of the cluster gas is estimated as

$$Z_{Fe}^{cl} = \frac{\int \frac{\gamma M Z_{Fe}}{1-\gamma} \phi(M) dM}{\int \frac{\gamma M}{1-\gamma} \phi(M) dM}\ , \qquad (16)$$

where Z_{Fe} is estimated from eq.(9).

Adopting the mass of observed hot gas in Coma within $5h_{50}^{-1}$ Mpc as $\sim 5.1 \times 10^{14} h_{50}^{-2.5} M_\odot$ (Briel et al. 1992), we derived the required combinations of (α, β) to reproduce all the gas in Coma by galactic winds, and plotted them in Fig.2(a). The thick solid line corresponds to a low-mass bound of $M_- = 10^4 M_\odot$, while the thin line, to $M_- = 10^6 M_\odot$. We adopt $h_{50} = 1$ here, but different values, such as $h_{50} = 2$ give essentially the same results. Comparing with the estimate by Trentham (1994) with the

assumption of $\gamma = const.$, our physically realistic values of γ imply more stringent bounds on (α, β); when $M_{-} = 10^4 M_{\odot}$ and $x = 0.95$, our required combinations of (α, β) are similar to his minimum case of $\gamma \sim 0.065 = const.$, and a Salpeter IMF and/or larger M_{-} give smaller values for (α, β). For instance, if the observationally allowed lower limit for the faint-end slope of the Schechter function is $-1.9 < \alpha < -1.7$ (Driver et al. 1994), Fig.2(a) implies $-0.55 < \beta < -0.37$, compared to $-0.42 < \beta < -0.27$ in Trentham (1994). Thus it becomes more difficult to reconcile with the observationally derived value of $\beta = -0.22 \pm 0.09$ for dSph galaxies (Kormendy 1990).

Figure 2(b) shows the resulting iron metallicity in Coma, in the hypothesis of dwarf galaxies as sources of the intracluster gas. The thick solid curve presents the case with parameters ($M_{-} = 10^4 M_{\odot}, \eta = 0.1$), indicating the very low abundance below 0.01 compared to the typically observed value ~ 0.2 (Hughes et al. 1988). Changing M_{-} from $10^4 M_{\odot}$ to $10^6 M_{\odot}$ (so that the gas ejection is prefrentially from more massive galaxies) or from $\eta = 0.1$ to 0.05 (so that t_{gw} is prolonged), simply doubles the iron abundance as $0.01 \sim 0.025$ and does not produce the observed high abundance. Thus we conclude that even if the number of dSph galaxies can supply the whole cluster gas, they are not the main sources of high metallicity observed in many clusters, because of the rapid loss of gas after the first burst of star formation. The smaller the low-mass limit of dSph galaxies, the smaller is the iron abundance, due to the increased contribution of smaller galaxies to ICM. The effects of Type Ia SNe, even if they contribute, do not provide more than three times iron of the value obtained here (Renzini et al. 1993). Therefore, we conclude that galactic winds from normal bright ellipticals are the main sources of intracluster metals (e.g., Matteucci & Vettolani 1988; Arnaud et al. 1992; Okazaki et al. 1993).

4. DISCUSSION

Here we discuss some implications of our results above. First, we discuss the origin of the intracluster gas, in the light of the constraints on the luminosity function of dSphs in clusters to be able to supply the hot gas, as plotted in Fig. 2(a). We consider sources for the primordial gas that can explain the X-ray observations. Then, in §4.2, we discuss the implications of our results on the iron abundance of the ICM in the case of dwarf galaxies being the dominant contributors.

4.1. *Origin of the ICM*

It has been argued by some previous workers that most of the X-ray emitting hot gas in clusters ought to be primordial, because the total gas ejected from bright ellipticals is insufficient to account for the large mass of hot gas. Okazaki et al.(1993), for exmaple,

estimated that less than 10% of the observed gas mass can be explained by gas ejected from large ellipticals. The primordial gas may have pervaded the cluster from the beginning, supplied by later gas infall (White et al. 1993), or gas which failed to accrete into local galactic potentials (Evrard et al. 1994). In contrast, Trentham's (1994) idea is that dwarf galaxies can supply most of the cluster gas via galactic winds, on the assumption that the fraction γ of ejected gas mass is constant for all galactic masses. Here, based on more realistic estimates of γ, we have found that in Coma, one needs smaller (α, β) than his case, *i.e.*, more unlikely values than allowed in previous observations ($\alpha \gtrsim -1.8, \beta \sim -0.22$). Although measurements of exact values of (α, β) still elude us, this hypothesis seems difficult to support. Moreover, as we shall explain below, gas in galaxies with $M \lesssim 10^6 M_\odot$ may not cool to form galaxies, and this makes the situation worse (Fig. 2a).

In the context of CDM theory, most of the baryonic gas is condensed into a number of small objects; as a matter of fact, the number can be very large due to the steep slope of mass function ~ -2. However, the temperature of small-scale virialized gas is below 10^4 K for all $M \sim 10^6 M_\odot$ and $\lesssim 1\sigma$ density contrasts of $M \sim 10^{7-8} M_\odot$, for which the cooling rate of the gas via radiation is essentially null (in the absence of molecular gas). Lacey & Silk (1991) showed that protogalactic objects with mass below $M \sim 10^{6-7} M_\odot$ never cool within the Hubble time, and this lower limit of the cooled mass is not changed in the presence of photoionization by diffuse UV background radiation (Chiba & Nath 1994). Probably such very small and dark objects are observed as Lyman α clouds in the intergalactic space, and the gas is stably confined in mini CDM halos (Rees 1986), with the temperature being kept $\sim 10^4$ K in the presence of photoionization (Efstathiou 1992). Therefore, there may be a number of small objects whose baryonic components have not cooled and that thus have failed to form stars.

We remark here that according to numerical simulations of cluster formation (see the review by White 1995), small-scale structures, which were present in earlier times, disappear due to mergings and tidal forces in the progress of hierarchical clustering, and the final output is a regularly structured cluster with a smooth profile. It is thus likely that uncooled gas which was originally condensed into small objects is dispersed during hierarchical clustering, and heated up to the virial temperature of the cluster after the collapse of the cluster as a whole.

If this is the case, we should add this uncooled primordial gas which is originally resident in small scale structures, $M_{uncooled}$, to the cluster gas. We estimate this as,

$$M_{uncooled} = \frac{N^*}{\phi^*} \int_{M_{lim}}^{M_-} \frac{gM}{1-g} \phi(M) dM \, , \tag{17}$$

where M_{lim} denotes the lower limit for the mass of virialized objects. The dotted line in Fig.2(a) corresponds to the case of $M_{lim} = 10^2 M_\odot$ with $M_- = 10^6 M_\odot$, and is comparable

to the case of Trentham's upper limit, $\gamma = 0.33 = const.$ (the maximum baryon fraction in Coma). We note that this uncooled gas can account for about 90% of total cluster gas in this case, and more than 80% even when $M_{lim} = 10^4 M_\odot$ as plotted in Fig.3. Therefore, in order to reconcile the idea of dSphs supplying the intracluster gas, with the present observational lower limits for (α, β) based on realistic estimates of γ, it is important to consider the non-negligible fraction of uncooled *primordial* gas in the mass scale below $\sim 10^6 M_\odot$. Furthermore, we note that the slope of the corresponding galaxy mass function $\phi(M)$, given as $(\alpha - \beta)/(\beta + 1)$, is ~ -2.2 for $M_{lim} = 10^2 M_\odot$, which is roughly in agreement with CDM slope of ~ -2. On the other hand, without uncooled primordial gas, the slope is ~ -2.4 for $M_- = 10^4 M_\odot$ and ~ -2.6 for $M_- = 10^6 M_\odot$, which seem to be too steep.

Therefore, we propose the uncooled gas in small objects as an alternative candidate for the source of the primordial gas that can explain most of the intracluster gas. This may also agree with the observed trend that richer clusters hold more hot gas; small objects below $10^6 M_\odot$ may be more vulnerable to destruction in richer clusters, thereby providing more gas. It is however premature now to test this hypothesis from numerical simulations, because the existent calculations lack enough dynamic range (e.g., a gas particle mass in Evrard et al. 1994 is $\sim 10^8 M_\odot$). More sophisticated simulations including better resolution are required to check this possibility.

We note that Trentham (1994) used a universal value of α throughout the cluster, which need not be true. The dwarf galaxies near the central region of the cluster are more vulnerable to being torn apart by tidal forces than the dwarfs in the outer region, and this will mean that α varies with radius in clusters. It is possible that the dwarf galaxies contribute to the ICM gas more in the outer regions than near the central region. Babul & Rees (1992) have argued that the inhibition of galactic wind from dwarf galaxies in clusters (*after* the ICM has formed) may give rise to some observed differences between dwarf galaxies in the central regions and those in the outer regions of a cluster.

4.2. *Metallicity of ICM*

In the previous sections, we have argued that the metallicity of the ICM gas originates mostly in Type II supernovae, if the dwarf galaxies are indeed the sources of the observed hot gas. We suggest that the ratios of different elements of the ICM gas should provide a test of the hypothesis of the dwarfs as main contributors of the gas. It is interesting to note that some previous workers (e.g., Canizares 1988; White 1991) have already inferred the origin of the metallicity of ICM in Type II supernovae, from the observations of the ratio of iron to oxygen. The observed ratio of $[O/Fe]$ is known to be $(3-5)$ times the solar value, which is indicative of Type II supernovae. This is in contrast to the prevalent notion, from the models of galactic winds from large ellipticals, that the bulk of the iron is

produced in Type I supernovae, where the oxygen to iron ratio is much smaller than that in Type II supernovae. For example, the ratio $[O/Fe]$ predicted by Matteucci & Vettolani (1988) is as low as ~ 0.9, and in other models (e.g., David et al.1990) it is of the order ~ 1.5 (Okazaki et al.1990).

The dominance of Type II supernovae as the contributors to the metallicity of the ICM gas can be increased by further interactions between the galactic winds and the intracluster gas. It is possible that, if the explosions that ejected the gas out of the galaxies happen at the same epoch, then the ejected gas, now in the ICM, may inhibit further galactic winds from any dwarf galaxies that may have retained some fraction of its gas to undergo starbursts later. The heating time scale of the intracluster gas depends on the mechanism of heating (Sarazin 1988). If the ejected gas is heated in a time scale shorter than that of the later starbursts from the surviving dwarf galaxies, then, as Babul & Rees (1992) argued, the winds can be confined by the surrounding hot gas. They estimated that, if $(nT)_{ICM} \gtrsim 10^4$ cm^{-3} K, then the wind from galaxies of mass $M_T \lesssim 3 \times 10^9$ M$_\odot$ would not extend beyond the galaxy's dark halo. The gas in the wind in this case would cool and probably fall back on to the core. It is possible that this effect may inhibit the injection of metals from Type I supernovae, which begin to enrich substantially the parent dwarf galaxies after a few times 10^8 yr of the first generation of stars.

Since our estimates of the mass of iron of the ICM from dwarf galaxies fall short for clusters with large metallicities, it is necessary to take the large ellipticals into account in some cases. Although the importance of Type I supernovae in enriching the gas inside and in the galactic winds from large ellipticals has been discussed in the literature, it is still a debatable issue. It is possible that the gas inside massive galaxies and the gas in galactic winds are enriched by different sources. Detections of any signature of Type II supernovae origin of the ICM gas will not necessarily rule out contributions from large ellipticals, if Type I supernovae are found not to be important for enrichment in the galactc wind gas.

It is possible that in rich clusters, where tidal forces are stronger, the dwarf galaxies do not supply most of the gas in ICM, and the metallicity is larger because the intracluster gas is mostly enriched by large ellipticals. Poor clusters are indeed seen to harbor smaller amount of iron than rich clusters (e.g., Mulchaey et al.1993).

In any case, it is almost certain that further X-ray observations of metal lines, especially with *ASCA*, will be useful in elucidating the origin of the metallicity of the ICM.

5. CONCLUSION

We have discussed the hypothesis that gas ejected from dwarf galaxies in clusters can explain the observed intracluster gas. We have derived analytical expressions for the fraction of ejected gas, and the metallicity of the gas, and found good agreement with

previous numerical estimates. We have then calculated the metallicity of the resulting intracluster gas, and found that the hypothesis of dwarf galaxies as sources of the gas, is tenable only for clusters with very low metallicity. Additional sources, such as galactic winds from large ellipticals, are therefore needed to explain the existence of metals. We have not included the gas and metal mass from large ellipticals in our calculations, but only showed the deficiency of the hypothesis of dwarf galaxies as sources of intracluster gas, as this work is intended as a critique of this hypothesis.

We further point out that, in CDM models, the gas in small-scale structures, which is dispersed and incorporated as diffuse intracluster gas by the process of hierarchical clustering, can account for most of the observed hot gas. We suggest that this process is of particular relevance in explaining the origin of the intracluster gas, especially for rich clusters.

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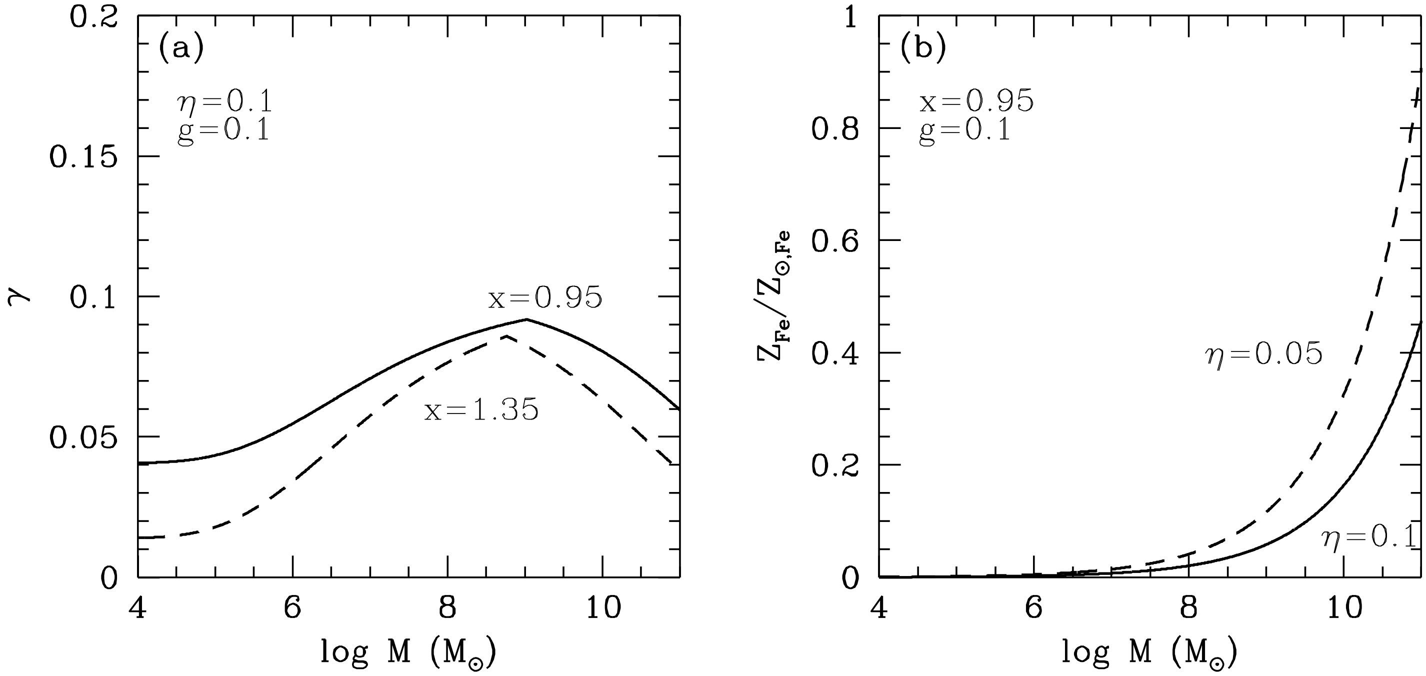
Figure Captions

Figure 1. (a) Fraction of gas mass $\gamma = M_g/M_T$ expelled from galaxies as a function of the present-day galaxy mass ($\eta = 0.1,\ g = 0.1,\ \tau = 1.0$). *Thick solid curve*: for an IMF with slope index $x = 0.95$. *Thick dashed curve*: for $x = 1.35$ (all curves are for $M_l = 0.1, M_{l,sn} = 8, M_u = 100M_\odot$). (b) Iron abundance of gas $Z_{Fe}/Z_{\odot,Fe}$ at the epoch of galactic wind as a function of the present-day galaxy mass ($x = 0.95,\ g = 0.1,\ \tau = 1.0$). *Thick solid curve*: for the fraction $\eta = 0.1$ of the supernova energy that is finally converted into the gas. *Thick dashed curve*: for $\eta = 0.05$.

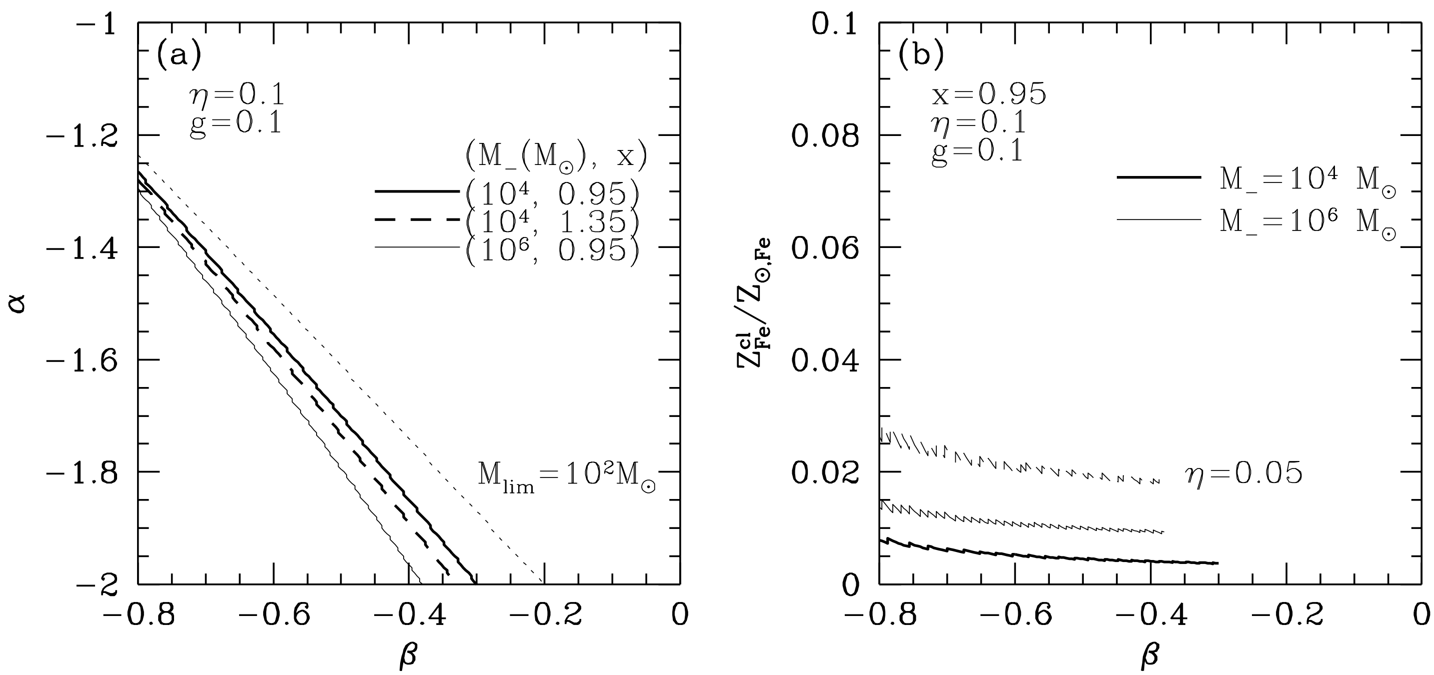
Figure 2. (a) Constraints on two parameters α (the slope of the dSph luminosity function at faint end) and β [$(M/L) \propto L^\beta$] to reproduce the observed hot gas in Coma by gas ejection from dSph galaxies ($h_{50} = 1,\ \eta = 0.1,\ g = 0.1$, the upper mass bound of dSph is $M_+ = 10^{11}M_\odot$). *Thick solid line*: for the lower mass bound of dSph being $M_- = 10^4 M_\odot$ and IMF index x of 0.95. *Thick dashed line*: for $M_- = 10^4 M_\odot$ and $x = 1.35$. *Thin solid line*: for $M_- = 10^6 M_\odot$ and $x = 0.95$. *Thin dotted line*: when the uncooled primordial gas in the mass range $M_{lim} = 10^2 M_\odot \sim M_- = 10^6 M_\odot$ given by eq.(17) is added to the expelled gas plotted as *thin solid line*. (b) Predicted iron abundance of ICM in Coma, $Z^{cl}_{Fe}/Z_{\odot,Fe}$, if all of the gas mass is enriched within dSph galaxies ($x = 0.95,\ g = 0.1,\ M_+ = 10^{11}M_\odot$). *Thick solid curve*: for $M_- = 10^4 M_\odot$ and $\eta = 0.1$. *Thin solid curve*: for $M_- = 10^6 M_\odot$ and $\eta = 0.1$. *Thin dashed curve*: for $M_- = 10^6 M_\odot$ and $\eta = 0.05$.

Figure 3. Fraction of uncooled gas erased from low-mass objects $M_{lim} \leq M \leq M_- = 10^6 M_\odot$ in Coma ($\eta = 0.1,\ g = 0.1,\ x = 0.95,\ M_+ = 10^{11}M_\odot$).



(a)
η=0.1
g=0.1
x=0.95
x=1.35
γ
log M ($M_\odot$)
(b)
x=0.95
g=0.1
η=0.05
η=0.1
$Z_{Fe}/Z_{\odot,Fe}$
log M ($M_\odot$)

Fig.1



(a)
η=0.1
g=0.1
(M_(M⊙), x)
(10⁴, 0.95)
(10⁴, 1.35)
(10⁶, 0.95)
M_lim=10²M⊙
α
β
(b)
x=0.95
η=0.1
g=0.1
M_=10⁴ M⊙
M_=10⁶ M⊙
η=0.05
Z^cl_Fe/Z_⊙,Fe
β

Fig.2

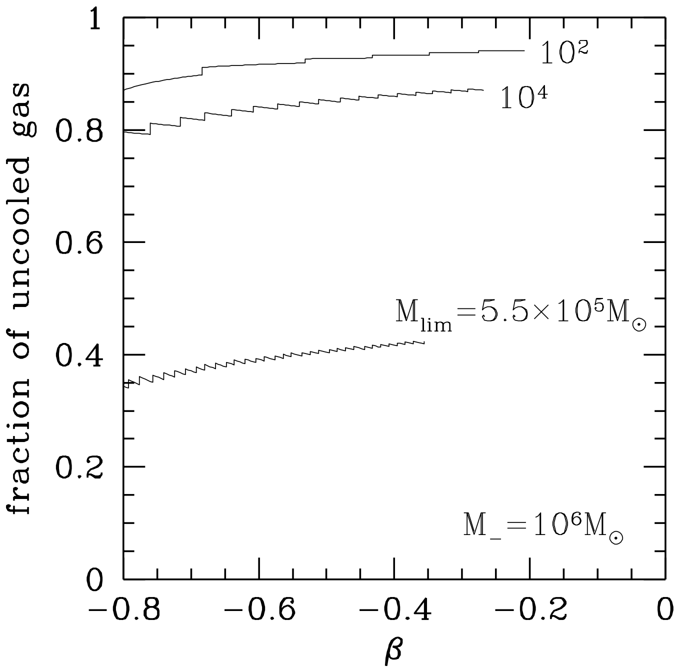

fraction of uncooled gas
β
10^2
10^4
$M_{lim}=5.5\times10^5 M_\odot$
$M_{-}=10^6 M_\odot$

Fig.3